

NSG-115
NSG-249

UNPUBLISHED PRELIMINARY DATA

MAGNETIC MEASUREMENTS NEAR VENUS

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FACILITY FORM 802
N65 15915
(ACCESSION NUMBER)
30
(PAGES)
CR 60354
(NASA CR OR TMX OR AD NUMBER)

(THRU)
/ (CODE)
30 (CATEGORY)

GPO PRICE \$ _____

OTS PRICE(S) \$ _____

Hard copy (HC) 2.00

Microfiche (MF) .50

ABSTRACT

15915

Mariner II magnetometer data are presented with a more thorough analysis and discussion than in a previously published preliminary report. No magnetic fields attributable to Venus were detected. An upper bound on the magnetic dipole moment of Venus M_V is estimated in several ways, subject to uncertainties regarding the dipole orientation and the nature of the interaction between the solar wind and the planetary field. Based only on Mariner not entering the Venus magnetosphere, the upper bound lies between $1/2$ and $1/6$ of M_E , the Earth's magnetic dipole moment. However, the absence of field fluctuations near Venus corresponding to the shell of disordered fields detected outside the Earth's magnetosphere by satellites and space probes shows that M_V is less than M_E by at least an order of magnitude and makes it probable that M_V is less than $M_E/20$. This result is consistent with qualitative predictions based on the dynamo theory of planetary fields. The energy flux of cosmic radiation above the Venus atmosphere, except perhaps for cosmic rays of the lowest energies, should everywhere approximate the intensity in the Earth's polar regions. Any radiation zone of trapped high-energy electrons is likely to be minor compared to the Earth's.

AUTHOR

INTRODUCTION

For several hours on December 14, 1962, a fluxgate magnetometer measured magnetic fields in the vicinity of Venus. Within several weeks some conclusions based on a preliminary analysis of the data were reported (Smith et al., 1963), but no data were published. The data, with a more thorough analysis and discussion, are presented below.

Our attempt to detect a Venus magnetic field and, if possible, to determine the magnitude, multipole order, and orientation of the source was motivated by important questions concerning the interior, upper atmosphere, and charged-particle environment of Venus. The information sought bears on the validity of the dynamo theory of planetary magnetic fields and the closely related question of the existence of a molten planetary core. The radial extent and temperature of the upper atmosphere depend, in part, on the ability of a planetary field to retain charged particles and to resist the approach of the hot, high-velocity solar wind toward the planet. The possible occurrence of aurorae and ionospheric and magnetic storm phenomena are bound up with the presence of a magnetosphere. The radiation environment, such as the distribution of cosmic rays and high energy solar flare particles in the upper atmosphere and of energetic particles trapped in Van Allen Zones, is directly related to the strength of the magnetic field. We return to these points after discussing the observations.

A trajectory near the Earth like that of Mariner near Venus would have provided a great deal of significant information about the geomagnetic field. However, no magnetic field that could be attributed to Venus was detected. Likewise, no perturbations in the plasma characteristics were detected (Neugebauer and Snyder, 1965), and no radiation belts were found (Frank, Van Allen, and Hills, 1963). This result does not require that Venus have no magnetic field, but only that the magnetic moment of Venus be weak compared with that of the Earth. An upper bound for the magnetic dipole moment of Venus can be estimated subject to uncertainties regarding both the orientation of the dipole and the nature of the interaction between a planetary field and the fully ionized solar wind. The interpretation of the Mariner data involves the methods and results of plasma physics, which, supported by satellite and space probe magnetic measurements near the Earth, indicate that planetary fields are compressed into a cavity, or magnetosphere, inside the streaming interplanetary medium.

DESCRIPTION OF THE MAGNETOMETER EXPERIMENT

The fluxgate magnetometer operates on the general principle of a second-harmonic type of magnetic amplifier (Geyger, 1954) (see Fig. 1 and 2). The sensing element is usually a hollow cylinder of high-permeability magnetic material surrounded by primary and secondary windings. An audio-oscillator connected to the primary windings is operated so that on each half cycle, the magnetic core is driven into saturation (no more magnetization is generated for an increasing primary field). The phases at which the core saturates are shifted asymmetrically by a steady magnetic field component along the sensor axis, thus producing in the secondary higher harmonics of the primary drive frequency. The second harmonic, the largest component, is approximately proportional to the field strength along the sensor axis; so it is detected, amplified, and used as the magnetometer output. By using two parallel sensors whose primaries are wound in opposite senses and whose secondaries are in parallel, the amplitude of the primary frequency in the output is greatly reduced while that of the second harmonic is doubled.

In a given magnetic field, the output of the electronics, a steady (dc) voltage, depends on the characteristics of the sensor (such as the permeability and geometry of the core) and of the electronics (such as the gain). The instrument must be calibrated by placing it in accurately known magnetic fields and determining the output. A coil system, such as a set of Helmholtz coils, can be used to generate a known, homogeneous magnetic field (Chapman and Bartels, 1940), which can be varied over the magnetometer operating range by adjusting the current in the coils. This procedure was used to calibrate the Mariner magnetometer before launch.

During the flight to Venus, the calibration of the Mariner magnetometer was checked for 3.696 min every 16.7 hr during normal spacecraft operation. A relay closure, commanded by the spacecraft, passed a small current from the regulated power supply of the magnetometer through auxiliary, "inflight calibration," windings on each of the three cores. The change in magnetometer output received at the Earth in response to the known change in field strength ($\sim 30\gamma$) gave the sensitivity of the apparatus. Because of a defect in the spacecraft command system, this calibration procedure was activated more often than was desired.

However, aside from adding slightly to the complexity of the data reduction, the data were not degraded by this accident.

The output of the Mariner magnetometer consisted of three analog voltages ranging between 1 and 6 volts. An output of 3.5 volts was obtained when there was no magnetic field directed along the sensor. The magnetometer detected the sign, as well as the magnitude of the field component, with the range from 1 to 3.5 volts corresponding to fields of one sense and the range from 3.5 to 6 volts corresponding to fields of the other sense. The magnetometer sensitivity was adjusted to give a nominal change of ± 2.5 volts for a field change of $\pm 64\gamma$. Automatic gain control was incorporated into the electronics in order to allow a greater range at reduced sensitivity. If a component of the ambient field approached $\pm 64\gamma$, the amplification of the channel sensing that component was automatically decreased by a factor of approximately 5. Thus, the dynamic range of the magnetometer was actually $\pm 320\gamma$. Nonlinearities in the system led to deviations from these nominal values, and both prelaunch, laboratory calibrations and postlaunch, inflight calibrations were used to determine the formula for conversion from voltage to field as a function of temperature.

The magnetometer analog voltages were converted to 8-bit binary numbers (between 0 and 255) by the Mariner Data Conditioning System (DCS) and telemetered. It was these digital numbers that constituted the primary data of the experiment. The uncertainty in the field measurement associated with the conversion to discrete numbers was nominally 0.25γ on the low range ($\pm 64\gamma$) and 1.25γ on the high range ($\pm 320\gamma$). When the data were acquired near Venus, the actual average values were 0.4γ and 2.3γ , respectively.

In space, the magnetic field at the sensor was the vector resultant of the interplanetary or planetary magnetic fields and fields associated with the spacecraft. In addition to spacecraft magnetic fields generated by current loops, many of the electronic and mechanical components, such as transistors, relays, transformers, the midcourse propulsion motor, and attitude control jets, were permanently magnetized. The three magnetometer sensors, mounted orthogonally inside a metal envelope, were located as far as possible from the main body of the spacecraft in order to reduce the contribution of spacecraft fields. The sensors were placed on the superstructure, just below the omnidirectional antenna, at a distance

~5 ft above the various subsystem assemblies. Since a Venus field might be manifested as a modest change from magnetic conditions in interplanetary space, the possible existence of magnetic-field changes associated with the spacecraft mode of operation near the planet was investigated. The spacecraft was operated in the laboratory in both the interplanetary and planetary modes prior to launch while the magnetic fields at the magnetometer sensors were monitored. The only effect observed was a characteristic, recognizable field change--having a magnitude of several gamma--associated with the radiometer scanning motion.

MARINER TRAJECTORY NEAR VENUS

The nature of the trajectory near Venus determines what kind of field changes can be seen. The distance of closest approach is the most significant parameter but other trajectory characteristics are also important. A trajectory that passes in the vicinity of the magnetic pole may give quite different data than a trajectory near the magnetic equatorial plane. If the spacecraft passes the planet on the side opposite the Sun, the chances of detecting a planetary field at a large distance are probably improved, because the magnetosphere is expected to have a long magnetic tail that extends to large distances from the surface in the antisolar direction.

The Mariner trajectory is shown in Fig. 3 in a Venus-centered coordinate system that is useful when considering the possible shape of the magnetic cavity. The axes are parallel to ecliptic coordinates that are useful in describing the interplanetary field. The right-handed, cavity-coordinate system R, T, N has its R-axis pointing away from the Sun along the direction in which the solar wind is expected to blow. Since nothing is known of the orientation of any possible magnetic moment of the planet, the T-axis is taken parallel to the plane of the ecliptic with its positive sense in the direction in which the planets move, and the N-axis is normal to T and R, being directed nearly toward the north pole of the ecliptic. (The angle between the N-axis and the polar axis of the ecliptic is just the ecliptic latitude of Venus or 1.45 deg.) The relation of these axes to the usual magnetometer axes (X_M , Y_M , Z_M) at this time was Z_M along R, $-X_M$ along N, to within 4.1 deg, and $-Y_M$ along T to within 4.1 deg. This 4.1 deg rotation is ignored in this presentation of the data, since it

introduces an error of only 7%--in general, less than the error of the digitalization. The trajectory near Venus, computed using Earth-based doppler shift measurements is estimated to be accurate to within 50 km.

If Mariner had encountered the Earth, instead of Venus, on a trajectory like the one shown in Fig. 3, the spacecraft would have entered the transition region between the interplanetary medium and the geomagnetic field at a point behind the Earth at a geocentric distance of 150,000 to 200,000 km, and entered the magnetosphere at 100,000 to 125,000 km. At a distance of 41,000 km (closest approach) the magnitude of the geomagnetic field is about 125 γ . The Earth's field at that point is relatively unperturbed by the solar wind, and the measurements would have provided an estimate of all three components of the Earth's dipole moment that was accurate to about 5 to 10%. A second penetration of the magnetosphere boundary and the transition region on the sunward side of the Earth near the noon meridian would have provided information on the shape and scale of the hydromagnetic flow pattern around the magnetosphere.

MAGNETIC DATA AT ENCOUNTER

The Mariner Data Conditioning System had two modes of operation. In the interplanetary data mode, the magnetometer outputs were sampled every 37 sec and in the encounter data mode every 20 sec. In each case, the three axes were sampled successively, with an interval of 1.92 sec between axes. The encounter mode was initiated by a ground command at 1340 UT, when the Mariner was more than 10^5 km from Venus. It was terminated at 2040 UT, after the radiometers had scanned the planet and before spacecraft visibility was lost at Goldstone--the only station capable of commanding mode changes at the Mariner, then at a distance of 5×10^7 km from the Earth.

In the encounter mode, the distance between triaxial field measurements was 140 km in a Venus-centered frame of reference and 750 km in a nonrotating, Sun-centered frame. Over 1200 samples of each component were obtained. Measurements made before and after encounter, over time intervals comparable to the duration of the encounter measurements, also contributed 1200 samples per component. In Fig. 4, each magnetometer reading is shown as a vertical line whose length corresponds to the

uncertainty introduced by the digitalization. The ordinates are decimal numbers. The conversion to gamma is indicated by the vertical bars that correspond to 10γ field changes. The sensitivities, which are $5.9\gamma/\text{DN}$ for the X-axis (i.e., B_N), $4.5\gamma/\text{DN}$ for the Y-axis (i.e., B_T), and $2.9\gamma/\text{DN}$ for the Z-axis (i.e., B_R), were determined from the inflight calibrations for this portion of the flight. Known field changes were produced in coils surrounding the magnetometer sensors, and the resulting changes in reading were recorded (see Table I). It is impossible to show on the graphs the zeros from which the interplanetary field is measured, since the spacecraft field is unknown. The changes shown by the figures are treated as changes in the interplanetary field, and these are all that are needed for our analysis. If some of the changes are due to changes in the spacecraft fields, this will only lower the limits that can be put on any effects due to the presence of Venus. The fact that the normal response was obtained from field changes produced by the inflight calibration mechanism shows that the magnetometer was operating and would have responded to changes due to the presence of Venus. It should be noted that the time scale used as the abscissa varies, depending on whether the data were acquired in the encounter or interplanetary mode.

The sensitivities given above are for the high-range (nominally 0 to $\pm 320\gamma$). When one of the solar panels failed, 36 days before encounter, a large change in the spacecraft field caused two axes of the magnetometer to switch to high range. The other axis, the X-axis, which is nearly along -N, was biased by the spacecraft field change to a value near the upper limit of the low range, and usually when the system went into the inflight calibrate mode, this axis switched to the low range. It also switched occasionally due to the changes in the interplanetary field. At the prevailing high temperature of the magnetometer, which reduced the sensitivity near the end of the range, the sensitivities of the two modes are comparable. In order to avoid complicating the analysis, numbers on the low range were converted to their equivalent values on the high range, and data taken in the inflight calibrate mode were converted to the equivalent values of the normal mode.

A cursory inspection of Fig. 4 shows that no field changes were observed that can be definitely attributed to Venus. The indication of a planetary field that could be seen at the greatest distance from the planet

Table I. A comparison of the step changes in the magnetometer output caused by the inflight calibration before, during, and after encounter.

Period		Number of calibration events in the period	Average change in digital output due to calibration pulse ^a			RMS deviations from averages		
From (day hr min sec)	To (day hr min sec)		X _M	Y _M	Z _M	X _M	Y _M	Z _M
319:12:18:40	326:02:22:15	19	-5.31	+7.36	+11.89	0.917	0.665	0.551
342:00:23:49	348:13:00:55	33	-5.15	+6.15	+11.09	0.608	0.556	0.771
348:13:42:00	348:20:30:52	1	-5.00	+7.00	+12.00	-----	-----	-----
(Venus Encounter)		1	-5.00	+6.00	+12.00	-----	-----	-----
348:21:18:02	355:11:54:09	18	-5.05	+6.11	+11.11	0.523	0.566	0.457
^a These changes correspond to field changes of 30.5, 30.4, and 31.3γ along the X, Y, and Z axes, respectively.								

should be the presence of fluctuations with amplitudes of several gamma and periods ranging from a few seconds to several minutes or more. Another indication that obviously should be checked for, even though one would expect to see it only after passing through the turbulent zone, is a smooth change in field strength characteristic of a dipole or quadrupole field. Thus, we must compare the data taken far from Venus with that taken from 1700 to 2040 UT, during which r_V , the radial distance from Venus, decreased from 70,000 to 40,000 km and increased again to nearly 50,000 km. The data obtained between 2040 and 2240 UT, when the distance had increased to 70,000 km, are equally relevant but definitely less useful because of the substantial transient associated with the mode change at 2040 UT. Comparison of the data shown in Fig. 4 with those taken during the previous week shows them to be typical interplanetary data, and there is no difficulty in accepting them as such and saying that they show no trace of the presence of Venus. However, it seems desirable to attempt to evaluate how much fluctuation and how much of a smooth change characteristic of the presence of a planetary field could be buried in the observations, concealed by the digitalization and the fluctuations provisionally ascribed to the interplanetary field.

First, consider the fluctuations. Near encounter, both components B_N and B_R show relatively long periods when all readings are of the same digital number. Thus, the maximum amplitude of fluctuations with periods less than about 20 min is less than the width of a single digital window; i.e., 2.9γ for B_R and 5.9γ for B_N . Even on the B_T axis, there are several periods of more than 5 min when the fluctuations have an upper limit of one digital number--or 4.5γ --although there are longer-period fluctuations of at least 4.5γ and possibly as large as 13.5γ , i.e., at least one digital number and possibly three. It should be particularly noted that the lower limit to the period of the fluctuations that can be detected is set not by the 37-sec interval between observations but by the approximately 1-sec time constant of the magnetometer. It is, of course, impossible to tell anything about the frequency of fluctuations with periods between 1 and 74 sec, but they cannot be present with amplitudes greater than a few gamma unless one makes the very implausible assumption that their spectra are built up of extremely narrow peaks very precisely placed. To summarize, we conclude that the fluctuations with periods between 1 sec and 3 min have

amplitudes less than 3γ on one axis, 5γ on a second, and 6γ on the third; and that the amplitudes could be considerably less on two of the axes.

Next, consider the possible smooth, long-period changes in one or more of the components that would be expected if Mariner had entered a dipole or quadrupole planetary field. The changes would have reached maxima near the point of closest approach and would have been reversed more or less symmetrically as r_V increased again. At the end, when only interplanetary and spacecraft fields were being measured, the observations should return to the same values as at the beginning. Our problem, then, is to deduce how large a smooth change of this kind could be buried in the observations. The most persistent digital value of B_N during this interval was 168. The occasional sporadic occurrences of 167 and 169 do not concentrate either at closest approach or at maximum distances as would be expected if they were symptoms of large scale field changes. Thus, the maximum change in this direction that is reasonable consistent with the data is 5.9γ . For B_T , the most common values near closest approach are 180 and the most common values at 70,000 km distance are 181. Because of the occasional occurrence of slightly larger (182) and smaller (179) values, a change in the field from about the transition between 182 and 181 to about the transition between 180 and 179 cannot be excluded. Thus, within the uncertainty due to the digitalization of the data, the largest reasonable variation in B_T is two digital numbers, equivalent to a field change of 9.0γ . The R-component values are mostly 116, and it appears unlikely that there was any smooth change larger than the width of this one digital number; i.e., 2.9γ . Thus, the largest change that might be attributable to Venus had a resultant of about 10γ . However, changes just as large or larger appear in the data while far from Venus, both before and after encounter. It should be noted in passing that if the conditions at 2000 UT had happened to be similar to those at 7000 UT or those at 0300 UT the next day, the limits on possible noise and smooth changes would have been very much larger.

ESTIMATE OF THE MAGNETIC DIPOLE MOMENT OF VENUS

By comparing our data with observations made near the Earth and appealing to theory, we can use these negative results to estimate an upper

bound to M_V , the magnetic dipole moment of Venus. Although the field could include contributions from higher-order magnetic multipoles, only the dipole moment, which should be dominant at large distances from Venus, will be considered. The negative observational results give no clue as to the orientation of the dipole moment. The dipole moments of the Earth, Jupiter, and the Sun (if it has a real dipole moment) are approximately parallel to their respective axes of rotation (Babcock, 1961; Chapman, 1948; Warwick, 1963). Presumably, this is a general condition associated with the dynamo mechanism, in which case the angle between M_V and Venus' rotation axis (apparently essentially the negative N-axis) is 20 deg or less. If this estimate is correct, the Mariner data were obtained near the equatorial plane. However, the very slow rotation rate of Venus should be cause for caution, and we shall consider estimates of the upper bound of M_V based on other orientations, including the possibility that M_V lies in the plane of the ecliptic.

Within the last year or two, the theory of the flow of the solar wind past a planet with a dipole field has developed to the point where it may provide a useful estimate of the upper bound of M_V that is consistent with our negative observations. An estimate in which much more confidence can be placed can be developed by scaling the spacecraft observations made near the Earth to allow for the effects of changes in the density of the solar wind and the magnetic moment of the planet.

First, though, it is of interest to consider an oversimplified, completely unrealistic, theoretical model. If interplanetary space were a vacuum and all field sources were inside Venus, an upper bound on M_V could be obtained easily. The field strength at magnetic latitude δ and radial distance r_V is

$$B = \left(M_V / r_V^3 \right) \left(1 + 3 \sin^2 \delta \right)^{1/2}.$$

Hence, if in the equatorial plane B must be less than 10γ when r_V is 41,000 km,

$$M_V < 6.4 \times 10^{24} \text{ emu} = 0.08 M_E,$$

where $M_E = 8 \times 10^{25}$ emu (i. e., gauss cm³) is the Earth's dipole moment. If the field must be less than 10γ at this distance along the polar axis, the upper bound on M_V is only half as great.

These estimates, although interesting, are not really relevant because of the existence of the solar wind, into which fields that originate outside the plasma cannot penetrate. The boundary between the planetary fields and the solar wind, which is called the magnetopause, comes where the pressure of the field, $B^2/8\pi$, just balances the dynamic pressure of the solar wind. To balance this pressure requires a field in the range from 100 to 200 γ , depending on the density and velocity of the wind. Thus, if Mariner had penetrated through the magnetopause, it would not be a question of seeing a 10γ field, it would have seen at least a 100γ field. Conversely, a more reasonable upper bound for M_V than that given above might be the maximum value that would leave the outer boundary of the region containing Venus' magnetic field inside the Mariner trajectory. Theoretical work on the shape and extent of this region has flourished recently and a number of models are available. All are characterized by the fact that the radius of the magnetopause, R , is connected with the other relevant quantities by a formula that equates magnetic pressure to the dynamic pressure of the solar wind; it reduces to

$$\left(M_V/R^3\right)^2 = nmV_W^2/F^6 \quad (1)$$

where F is a dimensionless function of order-of-magnitude unity that depends on the angles between \underline{R} , the radius to the point of observation, \underline{M}_V , the vector dipole moment, and \underline{V}_W , the vector solar wind velocity. The mass density of the wind is nm . The case in which the solar wind is a collisionless plasma whose ions and electrons are reflected specularly from the magnetopause and in which \underline{V}_W is normal to \underline{M}_V has been solved in reasonable exact form by Midgley and Davis (1963) and by Mead and Beard (1964). These solutions give $F = 0.66$ for the subsolar point and $F = 0.80$ for the position of Mariner's closest approach to Venus if \underline{M}_V is perpendicular to the plane of the ecliptic. To calculate the upper limit to M_V we take $R < 41,000$ km and a solar-wind momentum-flux density of 4.5×10^{-8} dyne cm⁻². The latter figure is based on the observations by

Neugebauer and Snyder (1965) of the solar-plasma density and velocity at encounter but is increased 20% above their figure to allow for alpha particles in the solar wind. We thus get $M_V < 0.35 M_E$ from $F = 0.80$. If M_V is normal to \underline{V}_W but not normal to the plane of the ecliptic, the upper limit on M_V could range from $0.64 M_E$ down to $0.30 M_E$. Actually, all these limits should be reduced somewhat since the cavity flares out, i.e., F increases, as one goes "downwind." The most severe constraint on the size of the cavity is supplied a bit downwind of the point of closest approach, as shown by Fig. 3 of Neugebauer and Snyder. No attempt to allow for this quantitatively will be made here, since a better estimate of M_V will be made below. Calculations dealing with the case in which the magnetic moment of Venus is not normal to the solar wind direction are based on a less valid model and have not been carried as far. However, the work of Spreiter and Briggs (1962) indicates that this makes no drastic change, and it is probable that the upper limit on M_V lies somewhere in the range $0.65 M_E$ to $0.30 M_E$.

The discussion in the previous paragraph is based on calculations in which it is assumed that the solar wind contains no magnetic field and that interactions between the particles are negligible. An alternative model that is sometimes used is the continuum approximation for hypersonic flow. This was developed for the case in which the collision mean-free path is much smaller than all the other characteristic lengths, which is certainly not true here; but it may represent reasonably well the situation in which the particles are organized into a fluid by the magnetic field and the flow velocity is high compared to the magneto-acoustic wave velocity. In this case, it is only necessary, according to Lees (1964), to multiply F by $(12/5)^{1/6}$ or to multiply each of the above estimates of the upper limit of M_V by $(5/12)^{1/2} = 0.62$. Even though some of the basic assumptions of this model are not particularly appropriate, it probably treats more realistically the momentum balance that determines the scale of the magnetopause than do the specular reflection models; and the correction factor should probably be used in any application of the specular reflection models.

Thus far, the discussion has centered on the extent of the magnetosphere, the region in which the magnetic lines of force lead back to the planet. But it is clear that a planetary magnetic field modifies the

interplanetary magnetic field to a considerably greater distance and, as recognized when we made our earliest estimate (Smith et al., 1963) of M_V/M_E , it is the extent of this outer region that fixes the upper limit of M_V . The essential point is that the solar wind must flow around the magnetosphere and that its flow pattern will be modified over a region whose size is proportional to the size of the magnetosphere. We are concerned with the supersonic flow of a nearly collisionless plasma containing a small magnetic field around a blunt obstacle, the magnetosphere. The shape and extent of the magnetosphere depend on the forces exerted on it by the fluid flow. Since the velocity of the solar wind is highly supersonic, the usual assumption is that there is a bow shock outside the magnetopause as indicated schematically in Fig. 5 (Axford, 1962; Kellogg, 1962). Outside this shock, the solar wind and its embedded magnetic fields should be completely undisturbed from their interplanetary state, unless high amplitude waves that can travel upstream at several times the Alfvén velocity are somehow excited in the shock. The Rankine-Hugoniot equations, which are based on the usual conservation equations, require significant discontinuities in the magnetic field and in the plasma in going across the shock. These should have been observable in the plasma data; whether they would be obvious in the magnetometer data depends on the magnitude of the various components, and this we do not know because of the unknown spacecraft fields. Although the theory of these collisionless shocks is quite incomplete, it is plausible that either the shock or the magnetopause might generate magnetic fluctuations (Dungey, 1958; Parker, 1958; Piddington, 1960; Bernstein, et al., 1964). In addition, the flow between the shock and the magnetopause could well be irregular, or even turbulent. This theoretical suggestion is amply confirmed by observation on satellites and space probes which have established that a thick shell of disordered fields surrounds the Earth's magnetosphere. Table II summarizes the available data (Sonett, 1960; Coleman, et al., 1960; Heppner, et al., 1963; Sonett, et al., 1963; Cahill and Amazeen, 1963; Ness, et al., 1964), and Fig. 6 shows typical plots in some cases. By far the most complete survey is provided by the IMP data of Ness, Searce, and Seek (1964), but the earlier data demonstrated the presence and approximate extent of this

Table II. Characteristics of magnetic field fluctuations inside the transition region as measured by magnetometers on various spacecraft.

Spacecraft	Date	Amplitude of the fluctuations (gamma)		Typical period (sec)	Geocentric distance (Earth radii)	Equatorial Sun-Earth-spacecraft angle ^a (deg)
		Typical	Maximum			
Pioneer 1	Oct. 1958	20	100	10	12.6 - 14.6	0
Pioneer 5	Mar. 1960	20	40	10	10 - 15	45
Explorer 10	Mar. 1961	20	20	300-1000 ^b	22 - 26 ^c	150
Explorer 12	Sept. 1961	25	50	5-15	8 - 13	0
Explorer 18 (IMP)	Nov. 1963	10-20	30	20-300	10 1/2 - 14 1/2	5
	Feb. 1964				12 1/2 - 17 1/2	-70
					17 - 28	-105

^aMeasured counterclockwise as viewed from above the North Pole.

^bShort period fluctuations were eliminated because data were averaged for 3 sec each 148.

^cThe magnetopause was detected at 22 R_E.

region. The variations are not quasi-sinusoidal but irregular, indicating that the frequency spectrum is broad.

Although the origin and nature of this region are not yet clearly understood, a similar physical condition should exist around any other planet that has a magnetic field. It should be a good approximation to assume that in going from one situation to another only the scale changes, the models being otherwise geometrically similar. The scale of the magnetopause is determined by the balance between magnetic pressure and the stagnation pressure produced by the momentum of the solar wind near the subsolar point. The shape of the shell of disordered field around the magnetopause is determined by the way gas flows around a blunt object and is determined mainly by the Mach number and the effective γ of the gas. The magnetometer observations of Ness, Searce, and Seek (1964) and the plasma observations of Bridge, et al. (1964) on IMP show that the relative proportions of the magnetopause and shock fit reasonably well the theoretical model of Spreiter and Jones (1963). Of course, day-to-day fluctuations in the momentum flux of the solar wind would be expected to produce considerable irregularity in the observations.

We are now in a position to make an estimate of the upper bound of M_V that is based on the most complete and realistic model of all those that we have considered. The basic observational fact is that nowhere along Mariner's trajectory past Venus were there any of the fluctuations in the magnetometer observations or changes in the plasma observations that would be expected if the trajectory entered the zone of irregular fields. In the previous section we saw that the maximum possible fluctuations along the various axes ranged between 3 and 6γ , whereas the expected fluctuations based on observations near the Earth are at the very least 5γ on each axis. Since these fluctuations are driven by the solar wind, they should be essentially as large near Venus. If the Mariner trajectory is compared with the Spreiter and Jones model (see Fig. 3 of Neugebauer and Snyder, 1965), one sees that the region where the shock would be encountered, if it would be encountered at all, is in a direction about 105° from the Sun-Venus line at a place where the distance from Venus is about 52,000 km. If the shock is to lie inside this point, then simple scaling of the Spreiter and Jones model indicates that the subsolar point on the magnetopause should be located inside 18,000 km and scaling the IMP data indicates

that it should be located inside 20,000 km. We now use $R = 20,000$ km and $F = 0.66 (12/5)^{1/6}$ to compute the upper bound of M_V from Eq. (1). The factor 0.66 in F is that appropriate for the subsolar point when the dipole axis is normal to the wind velocity, and the factor $(12/5)^{1/6}$, as discussed above, allows for the fact that there is a stagnation point rather than specular reflection at the subsolar point. The result is that the upper limit for M_V is 3.7×10^{-24} emu or $0.05 M_E$. If any other orientation of the dipole is considered, this upper limit would be affected by an amount that is difficult to estimate but is probably less than a factor of 2.

The above analysis depends only on the fact that Mariner II did not pass through a bow shock around Venus. Thus it could have been based on the plasma probe observations just as well as upon the magnetometer observations. It could not have been based on the energetic particle observations; these show only that the trajectory lay outside any magnetopause and hence give a substantially larger (i.e., less relevant) upper limit to the magnetic moment of Venus. It is true that Anderson, Harris, and Paoli (1964) and Fan, Gloeckler, and Simpson (1964) have observed electrons with energies in the neighborhood of 40 kev between the magnetopause and a point a bit outside the bow shock; but they are seen only sporadically and in a single brief encounter neither their absence nor their presence, which could be due to an interplanetary event like that of October 23, 1962, could be regarded as more than suggestive. At the time of the Mariner II observations, almost nothing was known of the bow shock of the Earth and the only phenomena known to provide an indication of the presence of a magnetosphere when well outside the magnetopause were the magnetic fluctuations described in Table II.

If Mariner II had passed into a magnetosphere, it is often assumed that this would be indicated as well by the plasma probe or the energetic particle detectors as by the magnetometer. However, only the magnetometer could provide information on the orientation of the dipole moment and hence on the magnetic latitude at which the observations were made. Also while it may seem plausible to assume that all magnetospheres are occupied by radiation belts, this could be a parochial point of view. It is true that both the Earth and Jupiter provide evidence for the assumption, but the synchrotron radiation from Jupiter indicates that its radiation belt has a higher energy density than that of the Earth. Until we understand

this, we must expect that some other planet's radiation belts could have a much lower energy density. If, for example, the rotation rate of the planet is important in determining the diffusion or acceleration of trapped radiation, Venus, with its low rotation rate, should be very different from the Earth.

The best estimate that can be made at present of the upper limit for the dipole moment of Venus is that it is one twentieth of the Earth's dipole moment. If one wishes to be conservative and consider less likely orientations of the magnetic moment as well as allow for the incompleteness of the theoretical models, it should be safe to say that the upper limit is one tenth that of the Earth. Of course the magnetic moment could be essentially zero as far as one can judge from the observations made by Mariner, or the field could be very irregular, in which case it could be strong in spots on the surface but fall off rapidly with distance from the surface.

DISCUSSION

In this section, some of the implications of the conclusion that $M_V < 0.1 M_E$ are considered.

This Mariner result is consistent with the expectations based on the dynamo theory of the origin of the Earth's field. Although no detailed theory is available, a fluid core is required and the rotation of the Earth is usually assumed to be an essential feature. Since Venus has a much slower rotation, it is very plausible that it should have a much smaller magnetic moment than that of the Earth, indeed, it should be expected that it is actually much smaller than our upper limit of $0.1 M_E$. If it had been found that $M_V \approx M_E$, it would seem necessary to assume either that the magnetic moment is insensitive to rotation rate or that the core of Venus has properties very different from that of the Earth.

If M_V is as large as $0.1 M_E$, the energy required for a cosmic-ray particle to penetrate close to the surface of Venus will be only one tenth of the critical energy required for the Earth at the corresponding magnetic latitude. For example, at the magnetic equator, protons with energies greater than 1.5 Bev should be able to reach the top of the atmosphere of Venus from the zenith as compared to the corresponding value of

15 Bev for the Earth. A 1.5-Bev proton reaches the top of the Earth's atmosphere vertically only poleward of 55 deg geomagnetic latitude. Thus, the cosmic-ray flux everywhere above the atmosphere of Venus will be similar to that above the polar regions of the Earth. "Polar cap absorption" should cover the entire planet rather than just the polar regions. If it turns out that M_V is substantially smaller than our upper limit, particles of still lower energy can reach the atmosphere, but this is not likely to be of great importance since the energy flux of cosmic rays drops off below these energies. Of course, the cosmic-ray intensity at the base of the Venus atmosphere will be much less than at the surface of the Earth because of the increased atmospheric absorption produced by Venus' much greater atmospheric mass per unit area.

If $M_V = 0.1 M_E$, a high energy radiation zone similar to the Earth's is still possible. It will have to be confined within the magnetosphere with a radial extent of $5 r_V$ or less, and perhaps will have a substantially different structure and density. The energy density of trapped particles cannot exceed the energy density of the planetary magnetic field, which will be 10^{-2} that of Earth. However, the energy density of electrons trapped in the geomagnetic field with energies above 50 kev is more than three orders of magnitude less than the geomagnetic field energy density (O'Brien, et al., 1962). If protons and lower-energy electrons are included, this limit may be even more significant.

If M_V is reduced below $0.1 M_E$, there will be correspondingly less possibility of trapping particles in the correspondingly smaller magnetosphere. However, M_V would have to be reduced to about $M_E/750$ before the magnetopause would be lowered to the top of the atmosphere. For smaller M_V , the solar wind and interplanetary field could interact directly with Venus' atmosphere. This would not be expected to have a profound effect on the atmosphere except at the highest levels, but it would make the magnetic situation more like that of the Moon than the Earth.

The Mariner observations definitely rule out the suggestion of Houtgast and Van Sluiter (1962) that Venus has a magnetic field that can affect the motion of the solar wind at a distance of 450-Venus radii. Even without direct observation, this is implausible since it would imply a magnetosphere 30 times as large as the Earth's and a magnetic moment 30,000 times as great.

ACKNOWLEDGEMENTS

The JPL magnetometer project engineer was B. V. Connor who was assisted by G. Reisdorf. Members of the Spacecraft Systems Division, including M. Goldfine, T. Harrington, R. Conover, and M. V. Ohanesian, assisted in measuring magnetic fields associated with the Mariner spacecraft. K. Heftman coordinated the machine reduction of the Mariner data; P. Conklin and L. Briglio were responsible for subsequent hand reduction and analysis. The three-axis fluxgate magnetometer electronics were designed and built by Marshall Laboratories of Torrance, California. The triaxial sensor was designed and built by Institut Dr. Forster, Reutlingen, German Federal Republic; technical coordination was provided by M. Gumpel of JPL. The experiment was supported by NASA under contracts NASw-6 (EJS), NsG 151-61 (LD), and NsG 249-62 (PJC).

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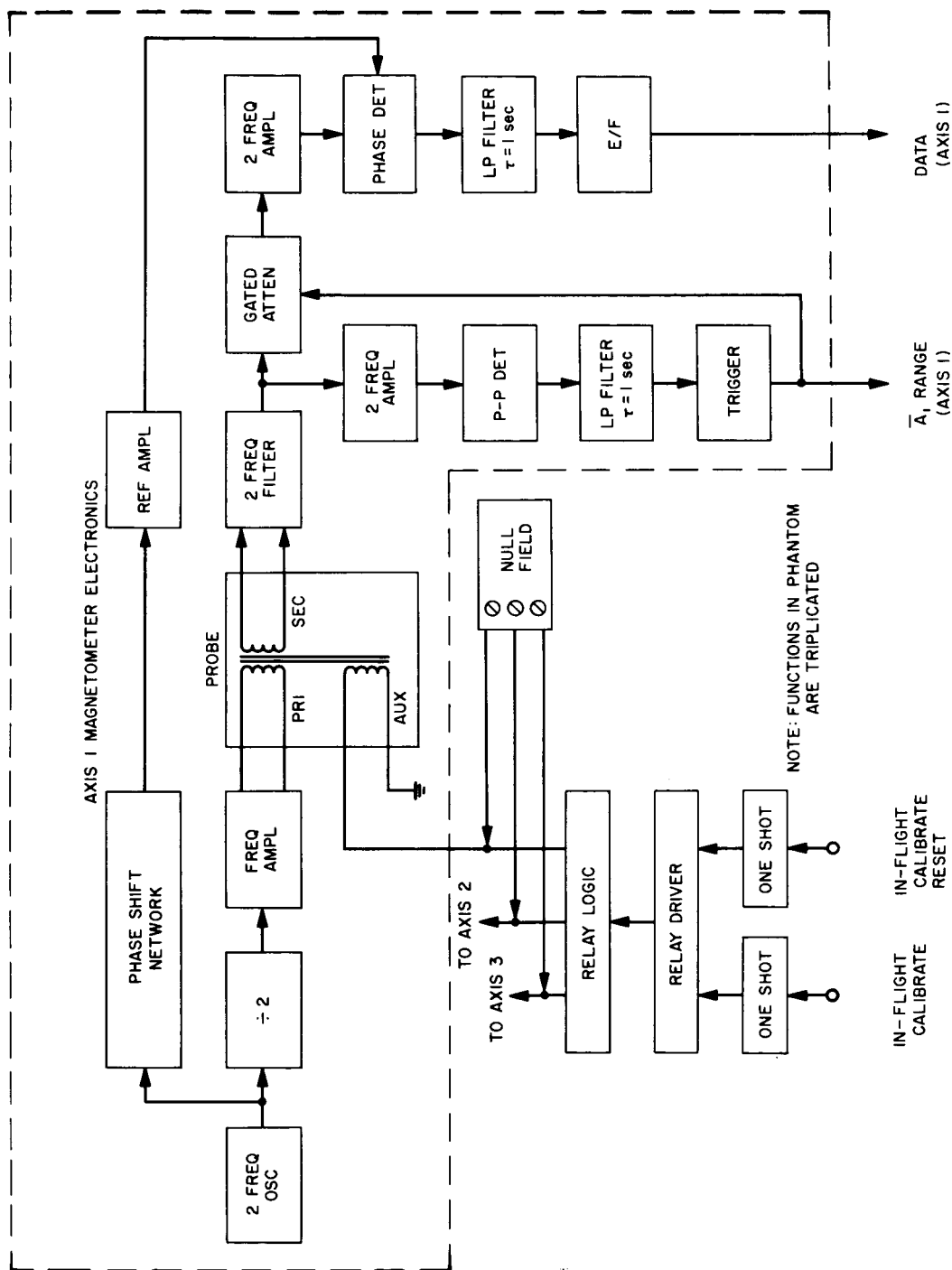


Fig. 1. Mariner II Magnetometer Block Diagram. The electronic block diagram for a single axis is shown. The horizontal flow lines at the top of the figure show the basic electronics, the drive and second harmonic coherent detector circuitry. The vertical flow lines in the lower half-figure are from left to right, the inflight calibration, automatic range control, and the analog output.

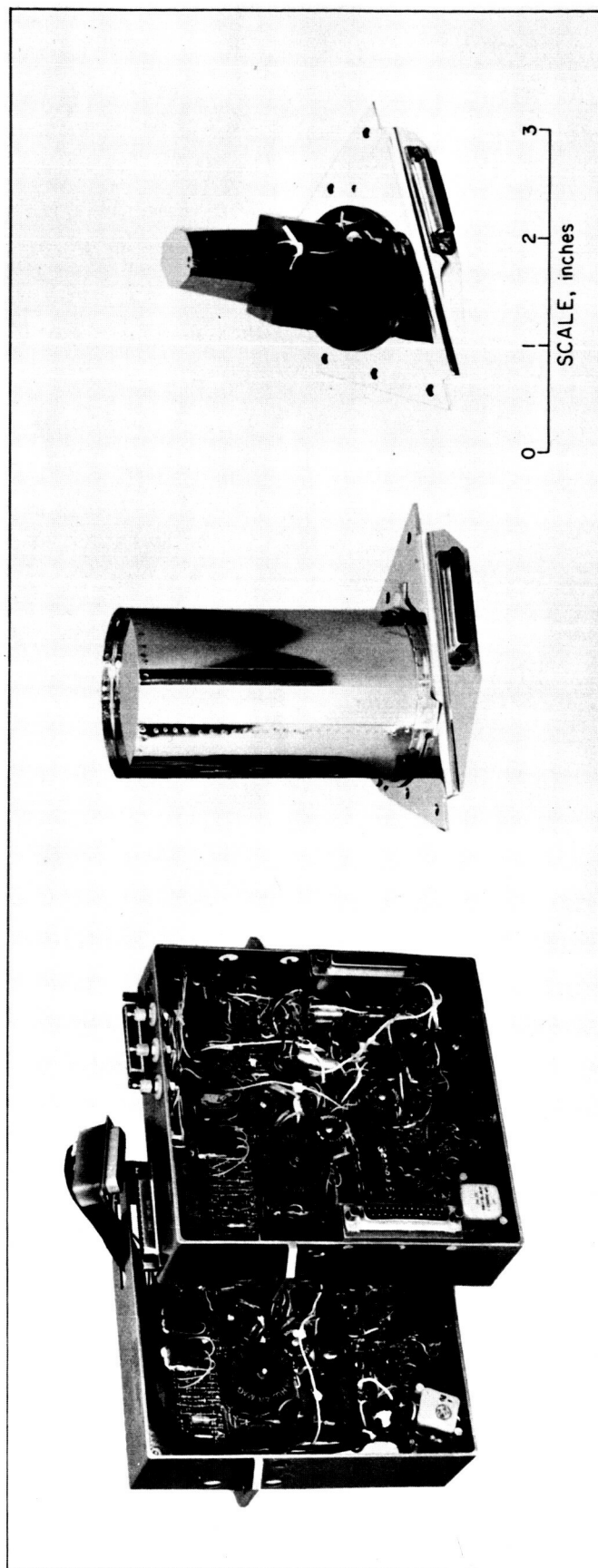


Fig. 2a. Mariner II Fluxgate Magnetometer. The two modules containing the magnetometer electronics are shown at the left. The triaxial sensors are shown at the far right, and the metal envelope in which they are enclosed appears in the center.

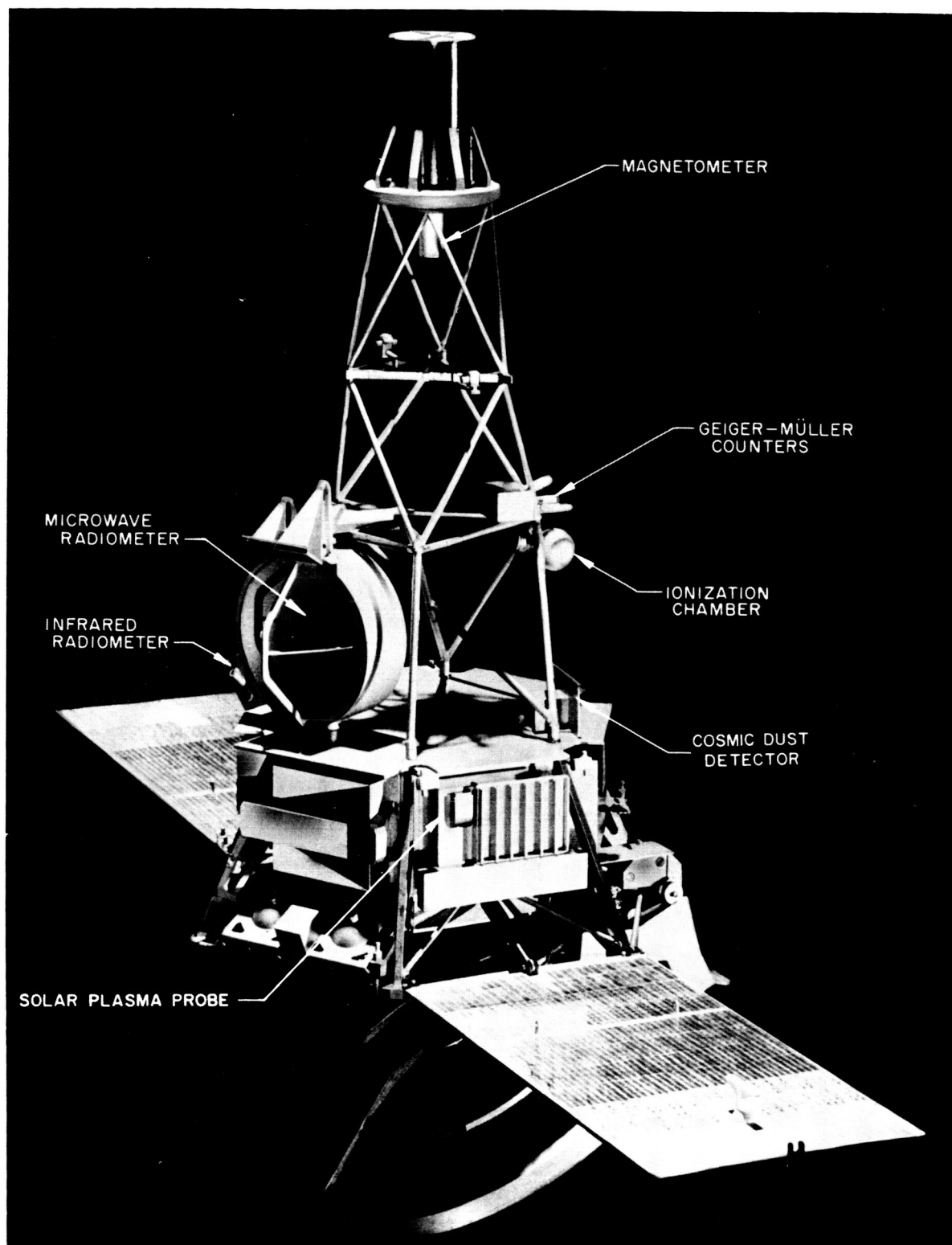


Fig. 2b. Mariner II. This photograph of the spacecraft shows the location of the magnetometer sensors and the locations of other experiments referred to in the text. The magnetometer electronics were located inside the main body of the spacecraft.

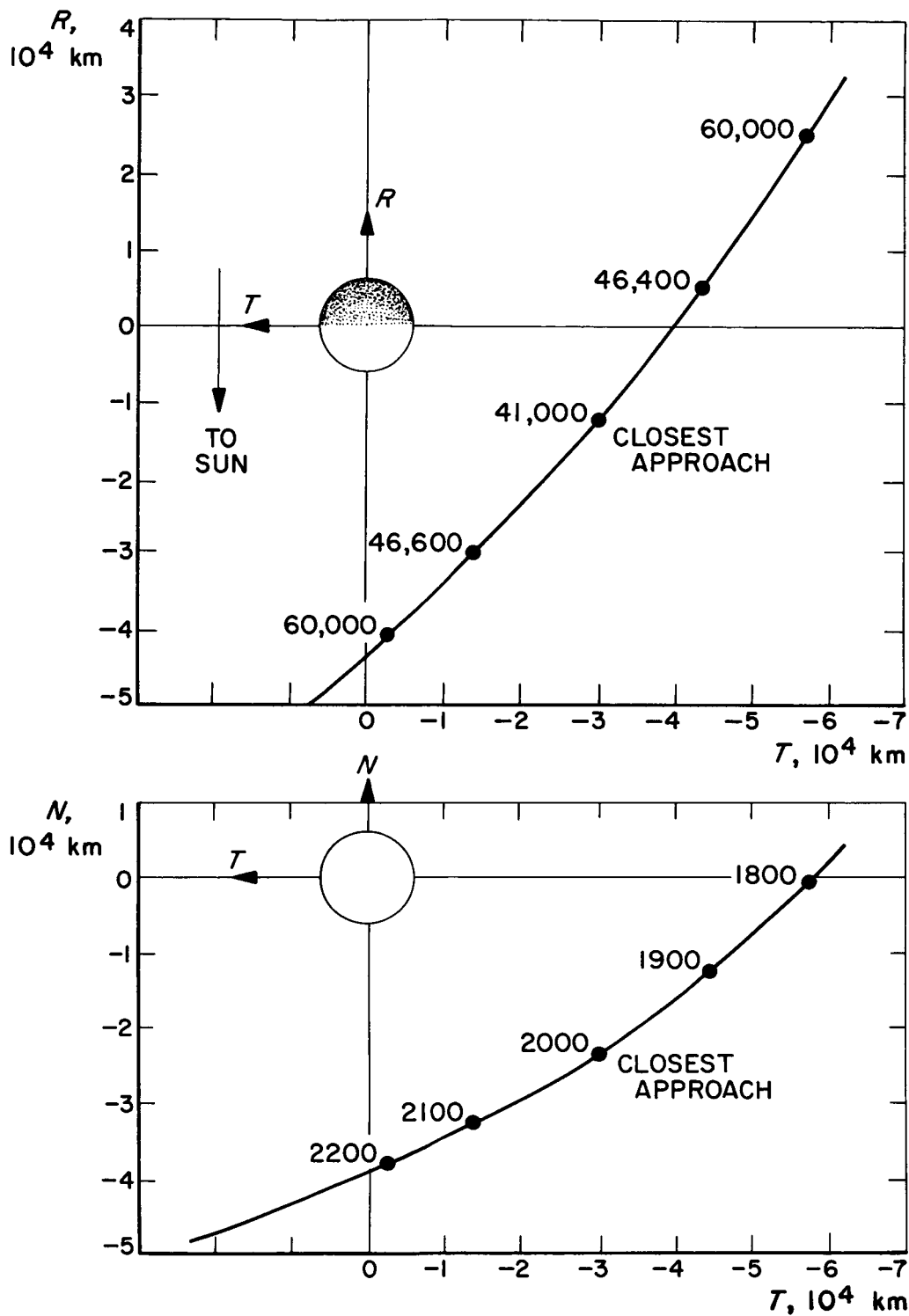


Fig. 3. Mariner II Encounter Trajectory. The view in the upper half-figure is essentially along the perpendicular to the ecliptic plane from above the north pole of Venus. (The angle between N and the ecliptic polar axis was only 1.5 deg.) The trajectory is viewed along the Sun-Venus direction from the Sun in the lower half-figure. The radial distances from Mariner to the center of Venus are shown in the upper half-figure for specific points on the orbit. The corresponding times (GMT) appear in the lower half-figure.

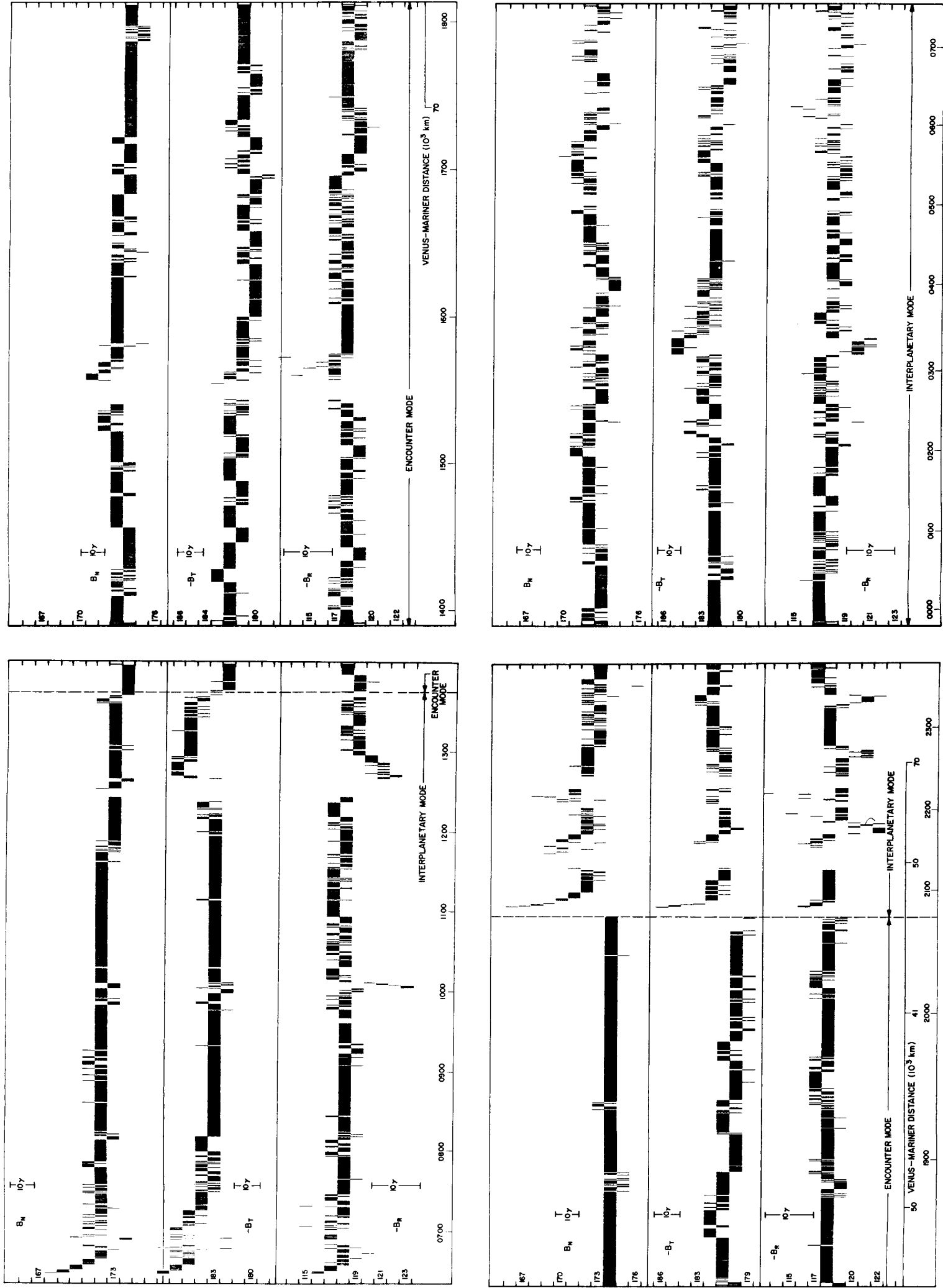


Fig. 4. Mariner II Encounter Data. Each magnetometer data point received during the interval on December 14 and 15, 1962, indicated by the abscissas, is represented by a vertical line extending over the range corresponding to a single decimal number. The ordinates are the decimal numbers. The conversion to gamma is indicated by the vertical bars. Only changes in the field have any significance since the spacecraft contribution is unknown. During the interval of closest approach, the distance of Mariner II from Venus is also shown.

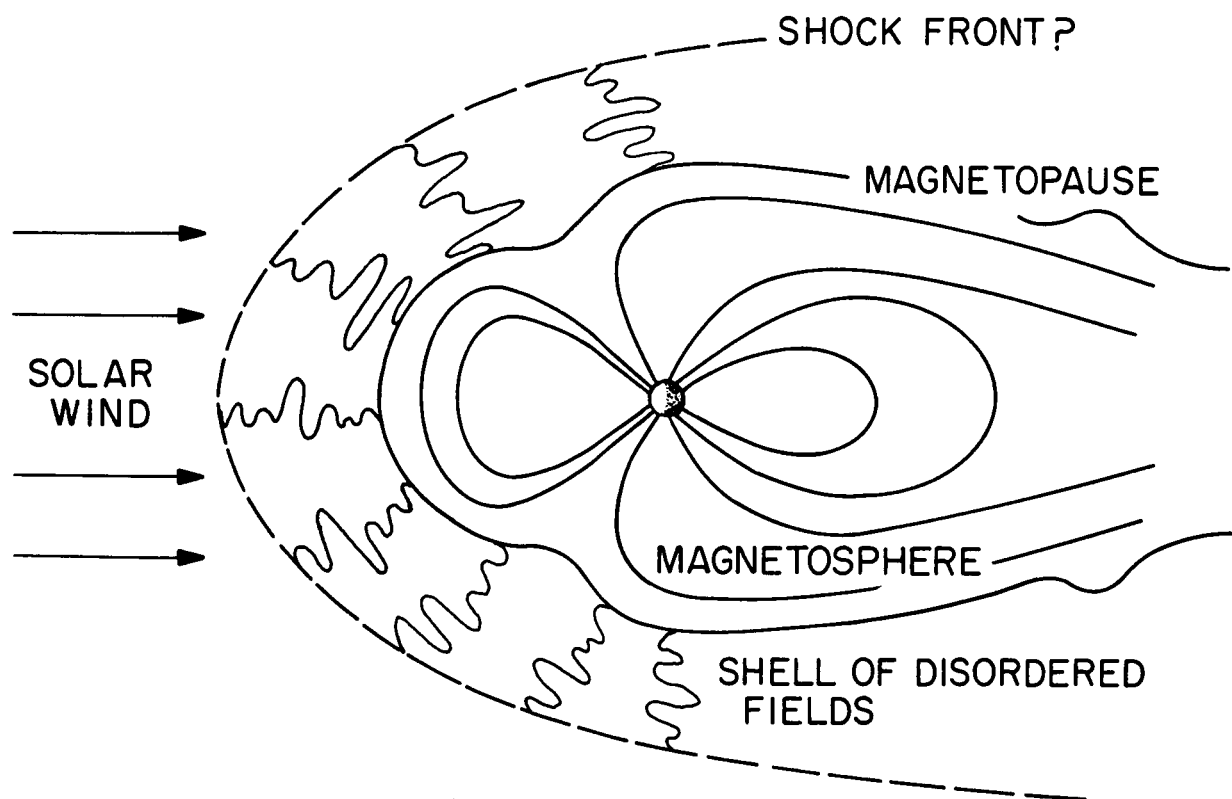


Fig. 5. Representation of the Earth's Magnetosphere Showing the Transition Region. In this representation the geomagnetic field is confined by the solar wind plasma to the interior of a cavity, which presumably closes on the downstream side of the Earth, although closure is not shown in the diagram. A thick shell of disordered magnetic fields surrounds the magnetosphere.

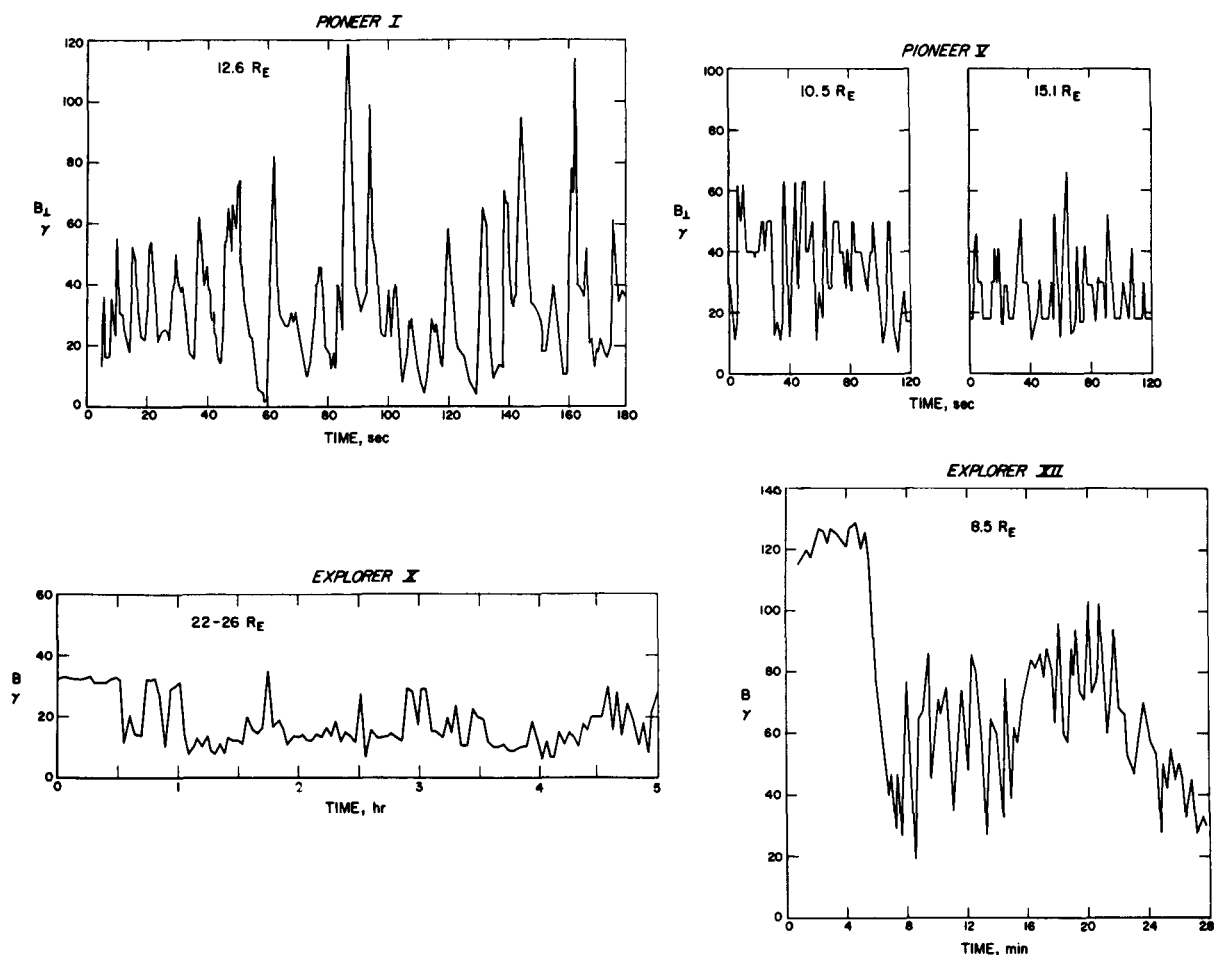


Fig. 6. Field Variations Observed Outside the Earth's Magnetosphere. Magnetic fields measured just outside the Earth's magnetosphere by four spacecraft are shown. The launch dates and orientation of the spacecraft with regard to the Sun-Earth line are given in Table II. The geocentric distance corresponding to each of the observations appears at the top of each sample. B_{\perp} is the component in the transverse plane approximately perpendicular to the Earth's equatorial plane and to the radius vector from the Sun.